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Investigating possible wind energy potential to meet the power shortage in Karachi

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ABSTRACT

Electricity is always considered as an important ingredient for development of a country. Energy deficit affects the growth rate of the country and causes discomfort to the consumer. The power shortage in Karachi, the largest city and economical hub of Pakistan, is highly hampering the progress of the city. Presently the energy deficit in the city is around 328 MW. This paper presents an analytical analysis of incorporation of small residential windmills to reduce the power shortage in Karachi. To estimate the wind energy potential in the city, four years wind data is collected from Pakistan Metrological Department (PMD) at various heights (10 m, 30 m, 50 m, 75 m and 100 m). The statistical calculations on wind data using SPSS software show that the city has an enormous wind potential available. A case study is also carried to show the effect of incorporation of small residential wind mills in power system. The results shows 1678 MW h of energy could be saved if 50% of residential consumers are equipped with small windmills. The paper also discusses the possible resistance in the introduction of small residential windmills in domestic sector. The potential benefits to the utility and consumers are also presented in this paper.

Contents

1. Introduction . . . 529
2. Overview of Karachi electricity supply company (KESC) . . . 531
3. Wind power potential calculations . . . 532
   3.1. Wind power density (W/m^2) calculations . . . 532
   3.2. Wind generator sizing . . . 533
   3.3. Effect of temperature, pressure and humidity on wind turbine performance (exergy analysis) . . . 533
4. Life cycle assesment of standalone PV-wind and diesel system . . . 534
5. Wind energy potential of Karachi . . . 536
6. A case study on wind potential analysis and utilization . . . 536
7. Challenges in implementing wind mills for domestic consumers . . . 538
   7.1. Cost . . . 538
   7.2. Proper site survey . . . 538
   7.3. Power quality . . . 539
   7.4. Zoning . . . 539
   7.5. Health impacts . . . 539
   7.6. Development of Standards for domestic windmill installation: . . . 539
8. Benefits to power utility company (KESC) and electricity consumers . . . 539
   8.1. Meeting power demand . . . 540
   8.2. Transmission line congestion and future cost . . . 540
   8.3. Eco-friendly environment . . . 540

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8.4. Carbon credit 540
8.5. Reducing line losses and increasing system capacity 540
8.6. A way to smart grid 540
8.7. Reliable power 541
8.8. Reduction in electricity bill 541
9. Conclusion 541
Acknowledgment 541
Appendix A. Questionnaire 541
References 541

1. Introduction

Electricity is always considered as the backbone for sustainable economical and industrial growth in any country. Consumers always demand reliable and low cost electrical power. Poor power reliability affects the consumers as well as the economy of a country. Pakistan is a developing country with an annual GDP growth rate 3.8% and the inflation rate is 14% for the year 2011 [1]. Currently the population of the country is 184 million (sixth largest nation in the world) and increasing with an annual growth rate of 2.05%. It is expected that with the current growth rate, the country will become the 4th largest nation by 2050 [2].

Presently, the country is highly dependent on import of oil for its domestic energy requirement and due to its large consumption in oil-fired power plants. For example, during the fiscal year 2010–2011, the total energy generated in the country was 102,484 GW h. However, the share of thermal electricity generation was 66,933 GW h (65.31%), hydel power plants were 32,223 GW h (31.44%) and nuclear power plants were 3,033 GW h (2.96%) [3]. Dealing with weak economy of the country, imports of petroleum products per annum costs more than $3 billion which further weakens the economy [4]. This problem will further aggravate in the future because national energy demand of the country is also increasing at an average annual rate of 5.67% [5]. Since 2007 to 2011, the installed generation capacity in the country has been increased from 19,696 MW to 23,142 MW (17%). However the un-diversified demand of the country has been increased from 16,958 MW to 22,765 MW (34%) [3].

Non availability of oil or reduced gas pressure in the country has also resulted in reduced capacity operation of existing thermal power plants. For example, the installed capacity of the country on July 1, 2011 was 23,412 MW, whereas the available capacity was only 19,669 MW. The main reason for non-utilization of total available capacity was the shortage of gas and inability of the government to finance the purchase of furnace oil, both for GENCOs as well as for IPPs. According to statistics, there was a reduction of more than 28% in gas usage for electricity generation in 2010–2011 over 2009–2010. The non-availability of the requisite gas from power utilities is a question mark for new thermal power generation projects [3].

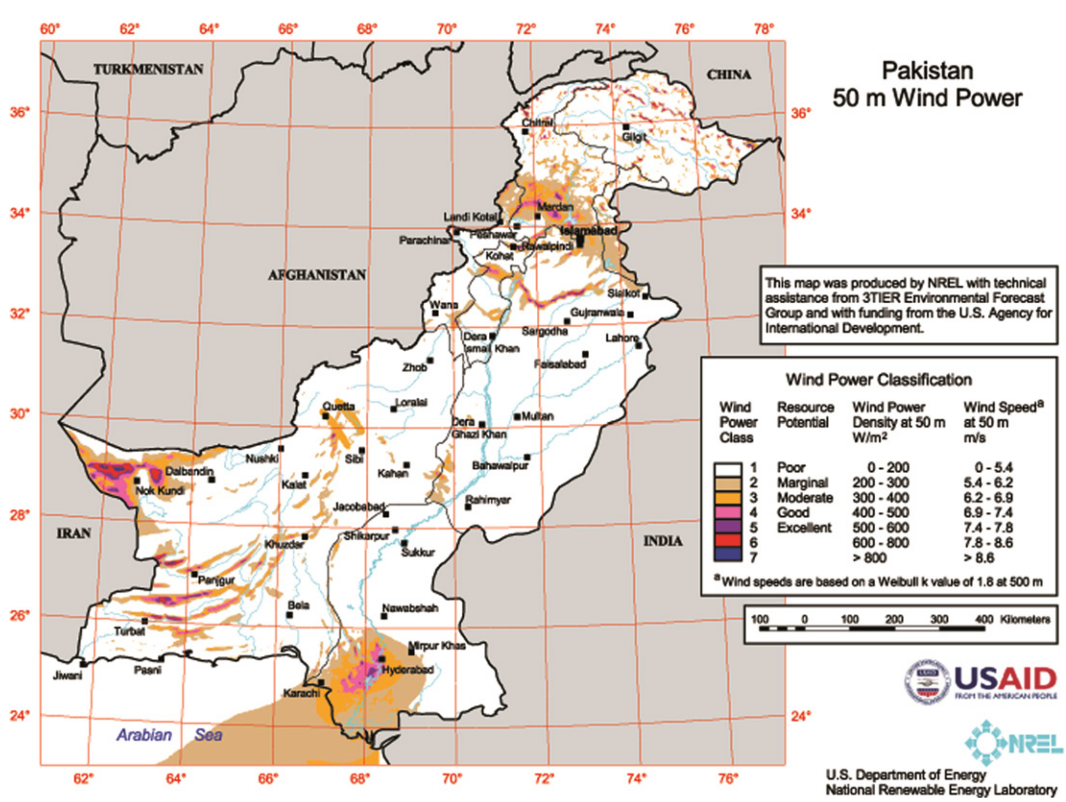

Fig. 1. Pakistan average wind speed classification.

On the other side, the country has several indigenous natural energy resources that need to be fully utilized. For example, Pakistan's coal reservoir is estimated 186 billion tones, which is among top 20 countries in the world. The Thar coal field in Sindh-Pakistan is the 5th largest single coal field in the world [6]. The country renewable energy potential (including solar, wind, tidal) is also exceptionally high in all major cities [7–9]. Efforts and sources are needed to fully utilize the renewable energy potential [2,10]. In 2006, the Government of Pakistan introduces the first Renewable Energy Policy for power generation. In 2010, AEDB got the status of autonomous body to create an environment in the country that is helpful to bring investment from the private sector in renewable energy [11]. Currently ARE sources are contributing only 25 MW whereas the country has a big potential of wind, solar, small hydel, biomass and waste power [12]. Other ARE technologies such as Geothermal, Tidal energy, Wave Energy, Biomass also exists but their potential is yet need to be determined [13].

The wind map developed by National Renewable Energy Laboratory (NREL), USA has indicated the availability of 346,000 MW wind potential in Pakistan. Fig. 1 shows the overall wind corridors available in Pakistan, the circle part is the area of Sindh province, which has a very high wind potential [14].

From Fig. 1, it can be observed that the country has a huge wind potential available. Studies indicate that there is a very promising wind energy potential of more than 50,000 MW with an average wind speed of more than 7 m/s at 80 m height in most of the coastal regions of Sindh and Balochistan [15]. The Coastal Belt of Pakistan is blessed with a wind corridor that is 60 km wide (Gharo Kati Bandar) and 180 km long (upto Hyderabad) [3]. Similarly in Karachi (the city of Sindh province), the wind potential recorded is in between 6.2 to 6.9 m/s[16]. Such a huge potential could be utilized to meet the local power shortage in the country.

After detailed data collection, AEDB have planned to produce 700 MW of wind power in Gharo, Sindh and a long term aim to inject 9.7 GW of wind power in national grid by 2030 [10]. For experimentation purpose in 2002, the government has installed eight 300 W turbines in Balochistan and six 500 W turbines installed in Sindh and it was concluded that it is cost-effective and technically possible option for electrification of remote villages[17]. In a latest research in China, it was concluded that the wind power units of rated capacity less than 100 kW are more cost effective as they require smaller initial investment and are easier to install, maintain and repair [18]. AEDB has also issued a letter of interest to a number of private sponsors for development of wind farms at the identified wind corridors in the coastal area of Gharo and Jhimpir. These projects include 49.5 MW, 50 MW and 56.4 MW wind energy power project by FFC Energy Limited, Three Gorges Co. and Zorlu Enerji Pakistan Limited at Jhimpir area (Thatta-Sindh). These Wind Power Projects are at advanced stages and expected to complete by mid of 2012 [3,19]. The present need is to explore the existing potential of the country, including coal, hydro and other renewable energy resources to reduce the demand–supply gap.

Karachi, one of the biggest cities and the financial hub of Pakistan is also affected by power shortage, besides having huge wind potential available. The cosmopolitan city makes a large contribution to the overall GDP of Pakistan. Power consumption in Karachi is also very high as compared to other parts of the country. The city handles 95% of total foreigner trade, 30% of industries located in the city and 90% of the head offices of financial institutions are located in Karachi. It is expected that the population of Karachi will reach 20.7 million in 2015 and 26.4 million in 2020 [20]. Like other cities of Pakistan, due to power shortage in the country, announced or unannounced 8 to 12 h daily load-shedding is common for all consumer categories [21]. In such a typical scenario, maintaining the economic growth rate with the same momentum is a major challenge for the city as well as in other part of the country.

This paper presents an analytical analysis of incorporation of small residential windmills and the possible affect on existing power system of Karachi. The basic concept of the paper is shown in Fig. 2. This strategy will reduce the power shortage as well as give some relief to the consumers in terms of electricity cost.

The paper is organized as follows. Section 2 gives an overview of Karachi Electric Supply Company (KESC). In Section 3, wind potential calculations in installation of wind mill is presented. In the same section, exergy analysis is carried out to show the effect of ambient temperature, pressure and humidity on windmill

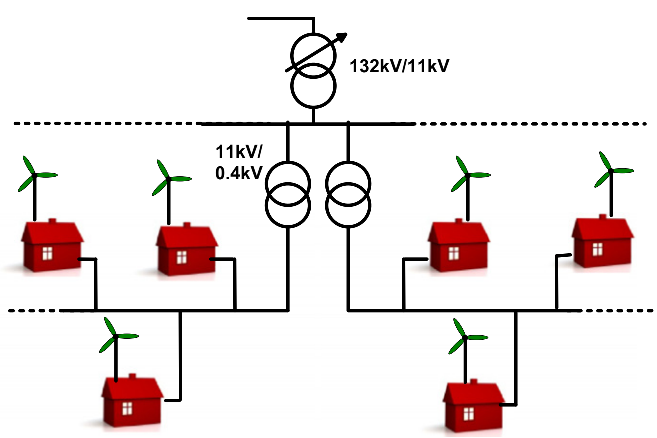

Fig. 2. Windmill incorporation for residential consumers.

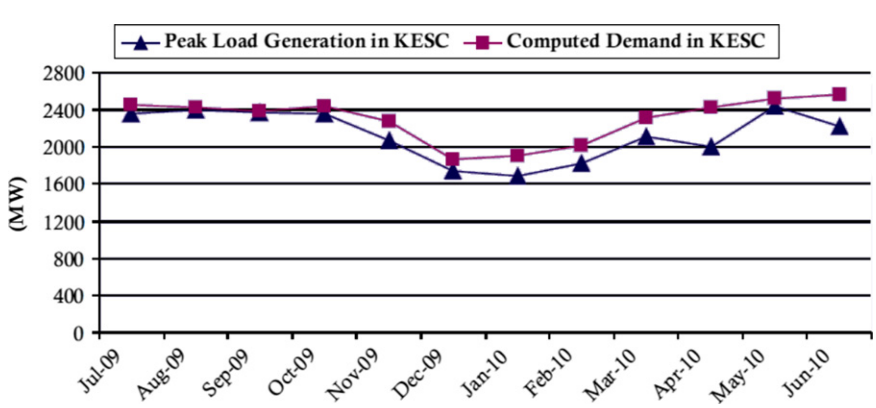

Fig. 3. Maximum demand and supply scenario in Karachi (For 2009–2010).

is presented. In Section 4, wind energy potential of Karachi is given. Section 5 presents the case study to show the effect of inclusion of residential windmill in managing demand–supply energy gap. In Section 6, the challenges in implementing windmills at residential level are given. While Section 7 presents the benefits of introduction of wind mills to the utility as well as to consumers.

2. Overview of Karachi electricity supply company (KESC)

Karachi is one of the biggest cities of Pakistan, having an overall population of more than 18 million [22]. Karachi Electricity Supply Company (KESC) is responsible to manage generation, transmission and distribution of electricity in the whole city. Other part of the country is looking after by Pakistan Electric Power Company (PEPCO). Both the systems are inter-connected via 500 kV and 220 kV transmission line for power interchange [23]. To improve the efficiency of KESC, the utility got privatized on 29 November 2005. KESC is the only vertically integrated utility in the country and supplies electricity to 2.32 million consumers, covering an overall area of 6500 km^2 [22]. On average, the demand of electricity in the licensed areas of KESC is 2500 MW. Moreover, the per capita electricity consumption in KESC system is 766 while in PEPCO area system, it is only 432 in 2010 [3].

KESC has the capacity to supply 2300 MW through its own generation and by procuring power from different external sources including Independent Power Producers (IPP) and National Transmission and Dispatch Centre (NTDC) which results in an average shortfall of 200 MW. However, most of the generation in KESC system is mainly composed of thermal power plants,

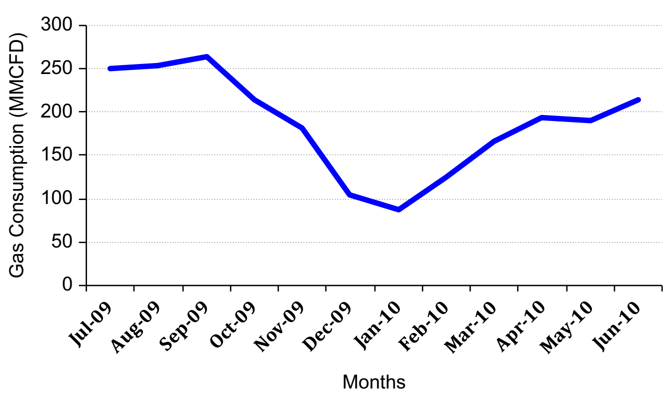

Fig. 4. Gas consumption analysis of KESC for 2009–2010 [22].

operated either on natural gas or oil resources. The total net capacity of thermal power plant in KESC system is 1618 MW. Moreover KESC is in the process of adding 560 MW Bin Qasim Power Station-II consisting of three gas turbines of 120 MW each. Thus the net available capacity of generation in Karachi is highly influenced by the reservoirs of heavy furnace oil and the availability of natural gas. Heavily relying on thermal power generations are also resulting in high tariff rates, as compared to other parts of the country. In last five years from 2006 to 2011, the cost of fuel (cost/kW h) has been increased by 70% (379.8 paisa/kW h to 648.00 paisa/kW h) [3].

The power situation in Karachi like other part of the country is also very poor. Fig. 3 is showing the demand and supply gap for the year 2009–2010. The monthly availability of gas supply to the KESC is shown in Fig. 4 for the same duration.

From Figs. 3 and 4, it can be observed that the pattern of demand–supply electricity is quite identical with gas-supply to the utility. The major reason for the non-availability of generation from KESC is heavily relying on gas supply from the authority due to high oil prices. Thus during the winter season (Oct–Feb) or in high gas demand period, the power generation from electricity utility is highly affected. The utility needs to follow the Scheduled Load Shedding (SLS) policy to manage the demand and supply gap. The SLS policy is based on the percentage of losses in that area. For example, in high loss areas, SLS duration is 4.5 h, low loss areas 3 h SLS duration, whereas no load shedding is being done for industrial and other strategic consumers.

In last five years, the maximum demand in KESC system has also been increased from 2349 MW (2007) to 2565 MW (2011). However during the last year 2010–2011, the percentage change observed was quite less 0.12% only. The major reason for lower power consumption increment was significant increase in fuel prices and the less growth in industrial sector due to existing law and order situation in the city. Table 1 is showing the actual and projected demand–supply scenario of KESC.

The category wise sale in GW h of KESC for 2010–2011 is shown in Fig. 5·[22].

From Fig. 5, it can be seen that the energy consumption in domestic load is higher than the industrial load. The main reason for higher power consumption in domestic sector is due to high population (18 million) in the city area. In the last decade, the less reliability of power from the utility has also forced the industries to have their own generations.

In addition to unavailability of generating power plants, fuel problem and high fuel prices, KESC is also suffering from high power losses in the system. In 2010–2011, the total Transmission and Distribution (T&D) losses excluding auxiliary consumption

Table 1
Surplus/deficit in demand and supply during KESCs system peak hours [24].

FY ending 30th June	Generation capacity (MW)		Demand during peak hours (MW)	Surplus/(deficit) (MW)
A: Actual figures				
2005	2109		2197	(88)
2006	2117		2223	(106)
2007	2283		2349	(066)/(max 395)
2008	2265		2443	(387)/(max 484)
2009	2403		2462	59
2010	2393		2562	169
2011	2237		2565	328
B: Projected figures				
30th June of financial year	**Planned generation (MW)**	**Projected demand growth rate (%)**	**Projected demand (MW)**	**Surplus (deficit) (MW)**
2012	2833	5.0	2825	8
2013	2913	5.0	2966	(53)
2014	3413	5.0	3114	299
2015	3713	5.0	3270	443

*Source: State of Industry Reports 2006 to 2011

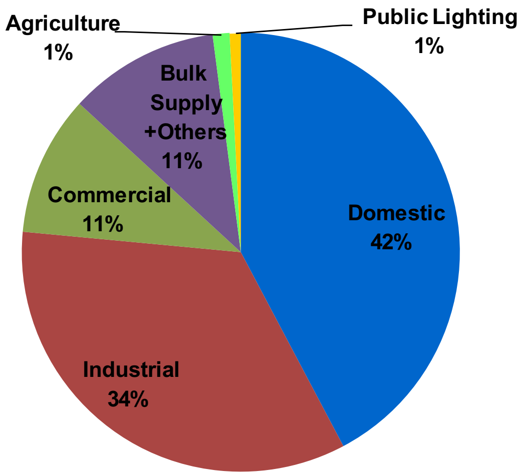

Fig. 5. Category wise sale (GW h) of KESC for 2010–2011.

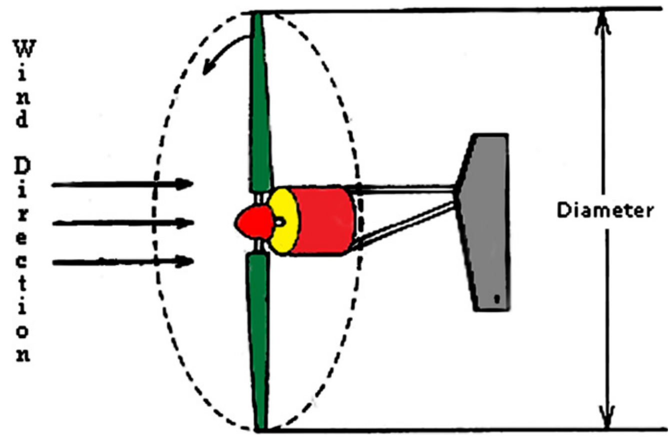

Fig. 6. Propellor-type rotor dimensions.

were 32.10%, which is quite significant. The major reason for such high losses includes technical losses, electricity theft and political influence. Although the new management of KESC are taking bold steps, which have resulted in decrease T&D losses from 34.90 % (2009–2010) to 32.10% (2010–2011). It has also been found that most of the system losses are occurring at distribution end due to electricity theft. KESC has started a policy of making alliance with local business group entities through a Distribution Franchise Agreement between KESC and strategic local partner. This will highly help in loss reduction, improving the quality of service and making the system more efficient [25]. KESC is also doing efforts to adopt such policies which will reduce the consumption of oil. Utility has signed an agreement with Bright Eagle Enterprise Group Limited (Hong Kong) for conversion of existing 1260 MW BQPS-1 to coal and adding more 1000 MW of coal based power generation in KESC's generation [26]. Further KESC has signed a five-year contract with Al-Abbas Sugar Mills Limited for purchase of 15 MW of electricity during the next five years from its coal-based power plant at Dhabeji. This will be the first coal-fired power plant connected to the KESC's network [27].

3. Wind power potential calculations

Wind speed plays an important role in determining wind potential at the given site. In this section, different approaches are presented to calculate the wind power density (W/m^2). Further the effect of environment on the wind potential calculations will be discussed.

3.1. Wind power density (W/m^2) calculations

Wind speed plays an important role in the site selection and windmill sizing. Two potential wind sites are compared in terms of the wind power density expressed in watts per meter square of area swept by the rotating blades of windmill, given by Eq. (1) [28]:

$$\text{Wind Power Density} = \frac{1}{2}\rho V^3 \ (\text{Watts}/m^2 \text{of the rotor swept}) \quad (1)$$

The available power from an air mass can be calculated using Eq. (2) [28]:

$$\text{Available Power in Wind} = \frac{1}{2}\rho A V^3 \ (\text{watts}) \quad (2)$$

where V is the velocity of air in m/s and ρ equals the air density in kg/m^3 (Taken as 1.225 at sea level), A is the area in m^2 swept by the blades, given by Eq. (3):

$$A = \frac{\pi}{4} D^2 \quad (3)$$

where D is the diameter measured from tip to tip of windmill blade as shown in Fig. 6.

The Eq. (2) will be hold good, if we extract whole of its kinetic energy and stop the wind in its track, which is impossible. There is a theoretical limit on the amount of power that can be extracted by a wind turbine from an air stream. It is called the Betz limit or power coefficient. This limit is 59.3% of power available, the complete derivation is available from [29]. Thus Eq. (2) will become:

$$\text{Maximum Power} = \frac{0.593}{2}\rho A V^3 \quad (4)$$

The power available from Eq. (4) could not be the output power, some mechanical and electrical losses will also occur. Thus an efficiency factor (E) is multiplied to get the electrical power output. The final expression is given by Eq. (5):

$$\text{Extracted Power} = \frac{0.593}{2}\rho A V^3 \times E \quad (5)$$

Value of E commonly lies in between 0.1 to 0.5 depending on wind mill design, given in Table 2, extracted from [28]. Thus there is a big scope to improve wind mill design and increasing the overall windmill efficiency.

Here in the above derivation, the wind speed is treated as the average wind speed and air density is considered a constant (1.225 kg/m^3) at sea level. However different methods are also available to calculate the wind power density and air density in

Table 2
Wind efficiency estimator (E).

Wind system	Efficiency (%)	
	Simple construction	Optimum design
Multi-bladed farm water pumper	10	30
Sailwing water pumper	10	25
Darrieus water pumper	15	30
Savoius wind charger	10	20
Small prop-type wind charger (up to 2 kW)	20	30
Medium prop-type wind charger (2 to 10 kW)	20	30
Large prop-type wind charger (over 10 kW)	–	30 to 45
Darrieus wind generator	15	35

literature [30–33], depending upon the recorded observations. For example Eq. (6a) is used when air density as well as corresponding wind speed is calculated for *n*th recording samples.

$$\text{Wind power density} = \frac{1}{2} \times n \times \sum_{j=1}^{n} \rho_j V_j^3 \quad (\text{Watts}/m^2 \text{ of the rotor swept}) \tag{6a}$$

where n is the number of wind speed samples, ρ_j and V_j are the *j*th readings of the air density and wind speed respectively. However Eq. (6a) will require tremendous data and a lot of computation. Thus there are some approximate methods to calculate the wind power density, one method is using a frequency distribution approach using Eq. (6b), which will reduce the computation time.

$$\text{Wind power density} = \frac{1}{2} \times \rho \times \sum_{j=1}^{n} \left[\left(\text{median } V^3 \text{ in class } j \right) \times \left(f_j \right) \right] \tag{6b}$$

where ρ is the air density and f_j is the frequency of occurrence in class *j*, using curve fitting, one can approximate the shape of the frequency distribution curve to find the wind speeds, wind power density can be calculated using Eq. (6c).

$$\text{Wind power density} = \frac{1}{2} \times K \times (\text{Mean wind speed})^3 \tag{6c}$$

where K is a value determined by the shape of the distribution pattern that the wind speeds follow.

Similarly for finding the exact air density at a given location, the following relations can be used in different given conditions.

1. When elevation '*z*' above sea level is given in m

$$\rho = 1.225 - \left(1.194 \times 10^{-4}\right) \times z \tag{7a}$$

2. When pressure and temperature data is given:

$$\rho = \frac{P}{RT} \tag{7b}$$

where P is air pressure (in Newton/m^2); R is specific gas constant (287 J/kg/Kelvin) and T is air temperature in degrees Kelvin.

3. When temperature data is given and pressure data is not available:

$$\rho = (P_0/RT) \times \exp(-g \times z/RT) \tag{7c}$$

where P_0 is standard sea level atmospheric pressure (101,325 Pascals), g is the gravitational constant (9.8 m/s^2) and z is the region's elevation above sea level (in meters)

In present analysis, monthly average wind speed is used to determine the wind power potential in Karachi using Eq. (5). However one can use either more accurate or approximate results, depending on the available data.

3.2. Wind generator sizing

The output power (P) from wind generator depends on the wind speed (V) as well as the diameter (D) of windmill blades. For a three blade horizontal axis machine, wind power is given by Eq. (8) [34]:

$$P = 0.20 \times D^2 \times V^3 \tag{8}$$

where P is expressed in watts, D is in meters, and V is in m/sec.

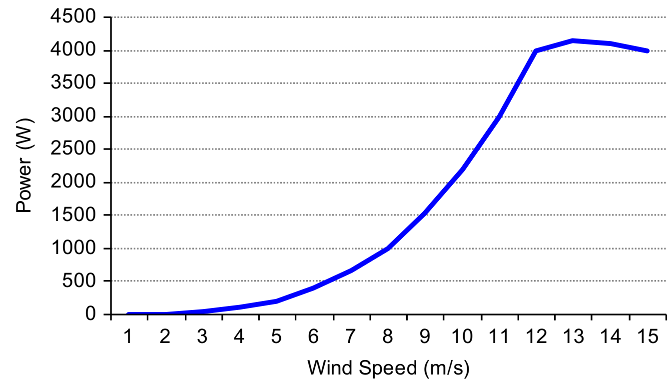

Fig. 7. Power curve of 4 kW wind machine.

In selection of size of wind generator, cut-in or crictical speed (V_{cr}) should be observed. Cut-in speed is defined as the minimum wind speed at which the wind turbine will generate usable power [35]. The generator output decreases to zero below V_{cr}. The relation between rated wind speed and cut-in speed is given by by Eq. (9) [34]:

$$V_{cr} = (0.15)^{1/3} \times V_r \tag{9}$$

where V_{cr} is the critical or cut-in speed and V_r is the rated wind speed in m/sec.

Study shows that the annual wind speed pattern in Karachi is same. The lower wind speed is observed during winter seasons Novemeber, December and January, while in moon soon seasons June, July, August and September, the wind speed is quite high. Studies have also shown that a 4 kW wind generator can be used efficiently throughout the year for all locations in Karachi. The cut-in speed of Karachi is quite good to support wind machines of 4 KW, however for larger machines the turbines could stall completely [34]. As an example, the power curve of 4 kW wind machine is shown in Fig. 7 [36].

From Fig. 7, it can be observed that the rated wind speed for 4 kW wind machine is 12 m/sec while the critical speed (V_{cr}) of this machine is 2.5 m/sec, which is quite reasonable from wind speed available in the city.

3.3. Effect of temperature, pressure and humidity on wind turbine performance (exergy analysis)

To observe the effect of environmental conditions on wind turbine output, exergy study is carried out. Exergy is a measure of the maximum useful work that can be done by a system interacting with an environment, which is at a constant pressure P_0 and temperature T_0. For computational case, the temperature T_0 and pressure P_0 of the environment are often taken as standard values, such as 25 °C and 1 atm. However, temperature and pressure may be specified according to measurements [37]. In present case study, T_0 is considered as 25 °C and P_0 is considered as 1 atm.

The kinetic energy or exergy content in the blowing air is given by Eq. (10):

$$\text{Exergy of kinetic energy} = \frac{V_r^2}{2} \tag{10}$$

where, V_r is the calculated wind velocity at height H. The wind velocity value can be estimated for different height by using the following Hellmann Eq. (11):

$$V_r = V_{ref} \left[\frac{H}{H_{ref}} \right]^{\mu} \tag{11}$$

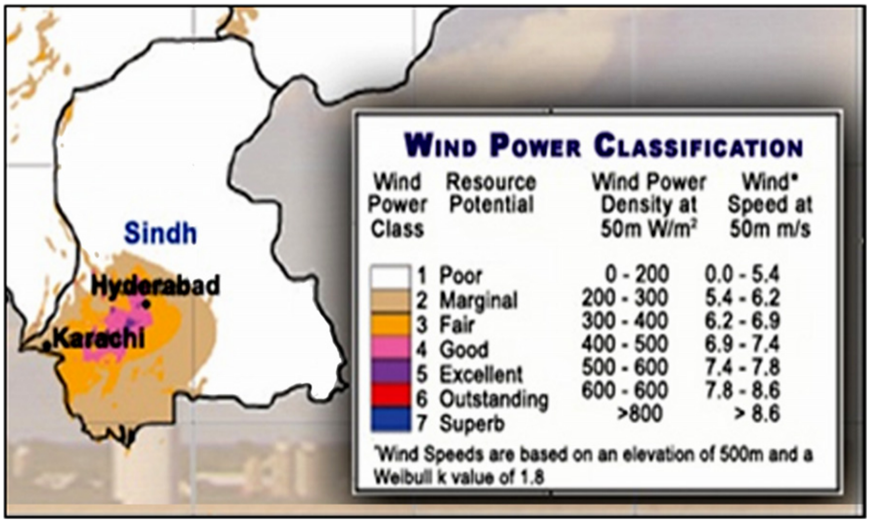

Fig. 8. Karachi wind speed classification.

where, V_{ref} is the wind velocity at reference height H_{ref}, Hellmann coefficient (μ) is a constant having value 0.28.

Two identical turbines at two different locations may differ in their output because of the different blowing air speed, quality of air (humidity) and different meteorological conditions (including temperature and air pressure). Here the effects of metrological conditions on wind performances are summarized below:

1. Effect of Ambient Temperature: The changes in ambient temperature affect the air density. With the increase in ambient temperature, air density decreases. Thus in case of wind turbine when the temperature increases, the turbine efficiency (or exergy efficiency) improves.
2. Effect of Ambient Pressure: In case of positive change in pressure ΔP (pressure difference between inlet and outlet of the turbine), the performance of wind turbine gets poorer and exergy efficiency decreases.
3. Effect of specific humidity: Specific humidity is the ratio of mass flow rate of water vapor in air to the mass flow rate of air. Humidity contents in blowing air also affect the turbine performances. With the rise of specific humidity in ambient conditions, exergy efficiency decreases. In addition, lower wind velocities have higher exergy efficiencies than higher blowing wind velocities in same specific humidity.

4. Life cycle assesment of standalone PV-wind and diesel system

In standalone system, wind energy could be one option to meet the residential demand. However, it is also very important to compare the wind energy with other sources like solar and diesel. For this purpose life cycle assessment study is carried out among diesel, wind and solar power generation. Life Cycle Assessment (LCA) analysis is carried out to get an overall environmental impact of the finish product, counted from the raw materials use till the end of-life product. Different researches [38–40] have been done for LCA of stand-alone diesel (or gasoline), PV-wind systems with batteries storage.

In [38], the author has compared the LCA of wind and diesel system and concluded with the following points:

1. In terms of the environmental impact of wind and diesel, the results of wind turbine is much better than the diesel system.

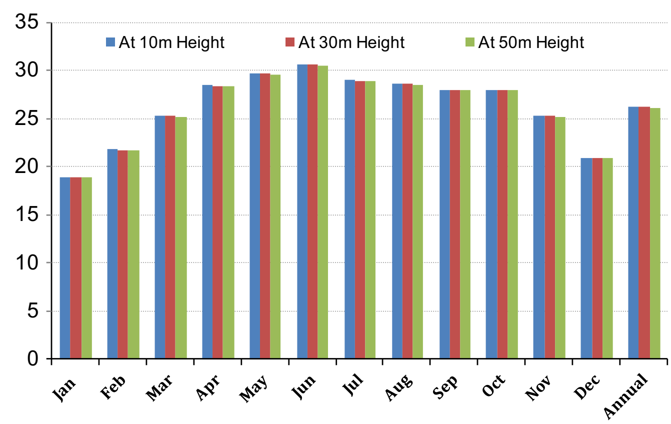

Fig. 9. Three years average monthly temperature variation from 2002–2005.

2. In terms of net energy input to the systems, the wind system consumes only (-55 kW h). However in case of diesel system (227,052 kW h) of net input energy is required.
3. In terms of economics, the diesel system was found cheaper than the wind system. In case of wind, major utilization occurs in terms of battery cost.

In [39], the author has compared the LCA of standalone hybrid PV-wind and diesel system and concluded with the following points:

1. In hybrid system, the inclusion of diesel generator results into better economical and environmental results, rather than only wind or PV system.
2. It is economically and environmentally better to use a diesel generator than a gasoline generator.
3. PV panels should be included in all systems even in windy places. Wind only system are not optimal.

In another study [40], the author has concluded the following key-points as major challenges in implementing standalone hybrid systems:

1. The renewable energy sources are suffering from poor efficiency particularly, solar PV modules.
2. The manufacturing cost of renewable energy sources needs a significant reduction because the high capital cost leads

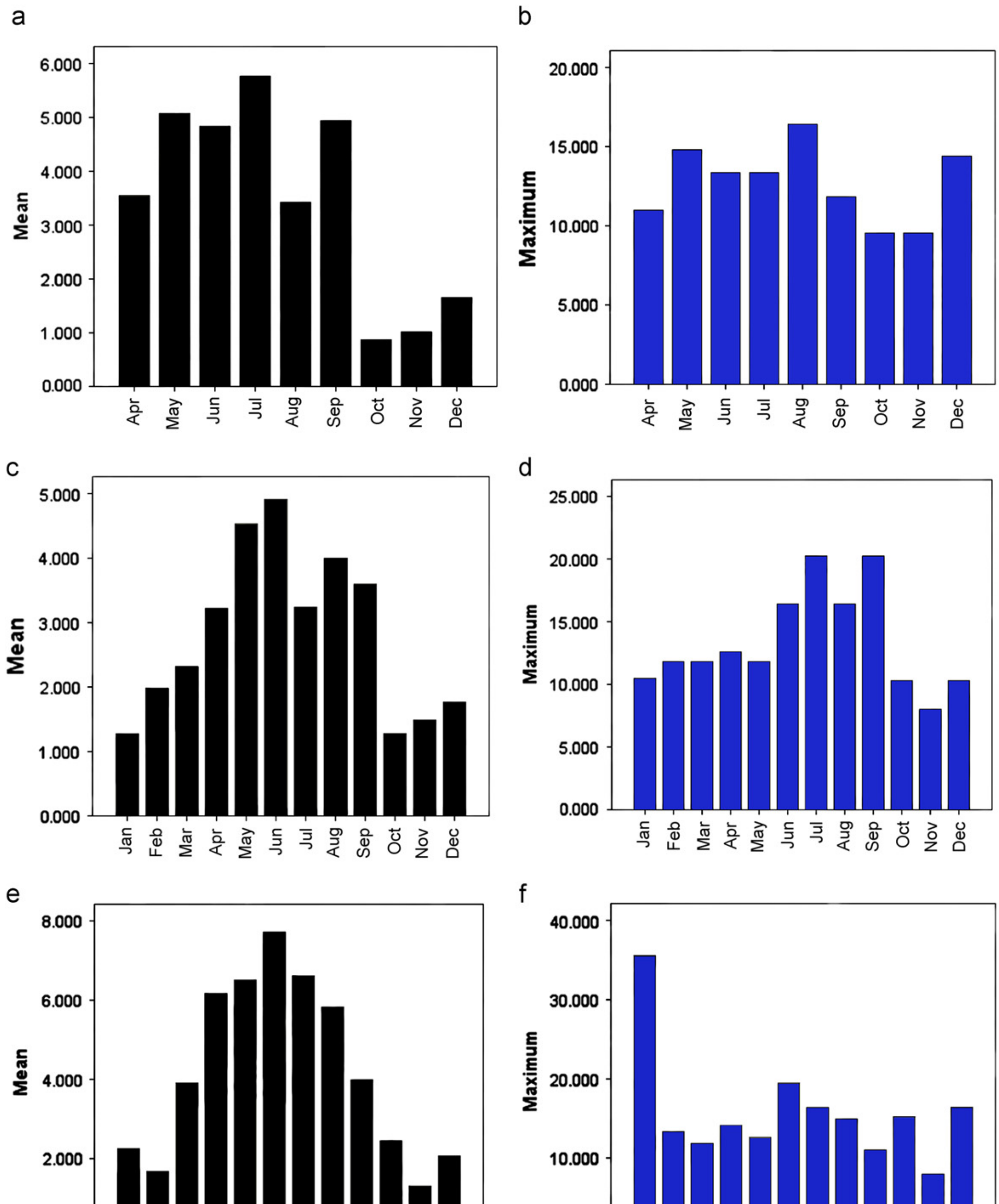

Fig. 10. Monthly wind speed (m/s) summary for year 2002, 2003 and 2004. (a) Monthly Mean Wind Speed (m/s) for 2002, (b) Monthly Maximum Wind Speed (m/s) for 2002, (c) Monthly Mean Wind Speed (m/s) for 2003, (d) Monthly Maximum Wind Speed (m/s) for 2003, (e) Monthly Mean Wind Speed (m/s) for 2004 and (f) Monthly Maximum Wind Speed (m/s) for 2004.

to an increased payback time. Cost reduction will provide an incentive to the industry to implement such systems.

3. There should be some standard for maximum power losses that could be occurred in power electronic converters (use for AC/DC conversion).
4. The life-cycle of storage devices need to increase through innovative technologies.
5. In case of hybrid renewable energy systems, proper protection systems need to be installed. Introducing renewable energy system will require an up gradation in the existing protection schemes.
6. These standalone systems are less adaptable to load fluctuations. Large variation in load might even lead to entire system collapse.
7. The disposal of storage devices are safety concerns for the manufacturers. The reduction in recycling cost or making interchangeable components can solve the problem of disposal of such devices.

These are the future challenges in implementing standalone hybrid power systems.

5. Wind energy potential of Karachi

Karachi is among that part of Sindh province (Pakistan) where a very high wind potential is available. It has been recorded that the cut-in speed in the city is quite good for producing wind energy [34,41]. According to NREL studies, the wind power classification of Karachi is shown in Fig. 8.

From Fig. 8, it can be observed that Karachi's wind class lies in the range of 3 (fair) to 4 (good) having wind speed 6.2–7.4 m/s. Such an enormous wind potential could be utilized to meet the power shortage in the city. Studies have also shown that the colder temperature reduces the air density and thus increases the energy utilization in a wind turbine system [41,42]. In Karachi, the higher blowing air temperature during the summer season (when power demand is very high) will also improve the efficiency of windmills and can help in reduction of demand-supply gap. The monthly average temperature variation for the Karachi is given in Fig. 9 for three years (2002–2005) [41].

For estimating the wind potential in Karachi, the wind data has been taken from the Pakistan Metrological Department (PMD) at the height of 10 m, 30 m, 50 m, 75 m and 100 m from 2002–2005 [43]. The site details are as follows.

Location: Jinnah Airport Karachi over Latitude: 24.91° and Longitude: 67.16°.

The wind speed observation is made on per second basis. The statistical analysis to find the mean–maximum speed, variance and standard deviation is carried out using IBM statistical software—SPSS. The monthly mean and maximum wind speed variation from 2002 to 2004 is also shown in Fig. 10. The detailed analysis of wind variation at 100 m height is given in appendix A (Table A1).

From Fig. 10, it could be observed that the overall wind speed in the city is quite good for windmill installations. However during winter seasons Nov–Dec–Jan, wind speed remains comparatively low as compared to other months. During these seasons, the Karachi power demand also decreases [22] due to decrease in ventilation load (air conditioner). The latest yearly wind data (from April 2010 to March 2011) is also collected at different heights from PMD on per second basis [43]. The corresponding monthly average wind speed and wind potential (W/m^2) at different heights is shown in Table 3.

From Table 3, it can be concluded that the wind potential is quite good and the variation in wind speed due to changes in tower height is quite low. To find the direction and quality of wind speed, monthly wind direction and wind rose-curve at 100 m height is also plotted on MATLAB (for year 2010–2011). A wind rose plot is a graphical polar representation which shows how wind speed and wind direction are distributed at a particular location over a specific period of time. The distance from the origin being proportional to the probability of the wind direction being at the given angle usually measured from the north. The directions of the rose with the longest spoke show the wind direction with the greatest frequency [44]. Results are shown in Fig. 11.

From Fig. 11, it could be observed that the overall wind speed is quite good particularly in the West and South direction of around 210°.

6. A case study on wind potential analysis and utilization

In present work, the possible affect of installation of windmill by residential consumer on power utility is calculated. For this

Table 3
Wind speed and wind potential at 10 m, 30 m and 50 m heights.

Height	10 m		30 m		50 m	
Months	Avg. wind speed (m/s)	Wind potential (W/m^2)	Avg. wind speed (m/s)	Wind potential (W/m^2)	Avg. wind speed (m/s)	Wind potential (W/m^2)
Apr'10	7.5	258.4	7.6	268.87	8.0	313.6
May'10	8.0	313.6	8.2	337.71	8.2	337.71
Jun'10	7.3	238.27	7.5	258.40	7.8	290.66
Jul'10	6.2	145.98	6.5	168.21	6.8	192.59
Aug'10	7.2	228.61	7.4	248.2	7.6	268.87
Sep'10	6.2	145.98	6.2	145.98	6.5	168.21
Oct'10	5.4	96.45	5.4	96.45	5.7	113.43
Nov'10	5.5	101.90	5.6	107.56	5.9	125.79
Dec'10	5.4	96.45	5.6	107.56	6.0	132.3
Jan'11	5.3	91.19	5.3	91.19	5.6	107.56
Feb'11	5.4	96.45	5.4	96.45	5.6	107.56

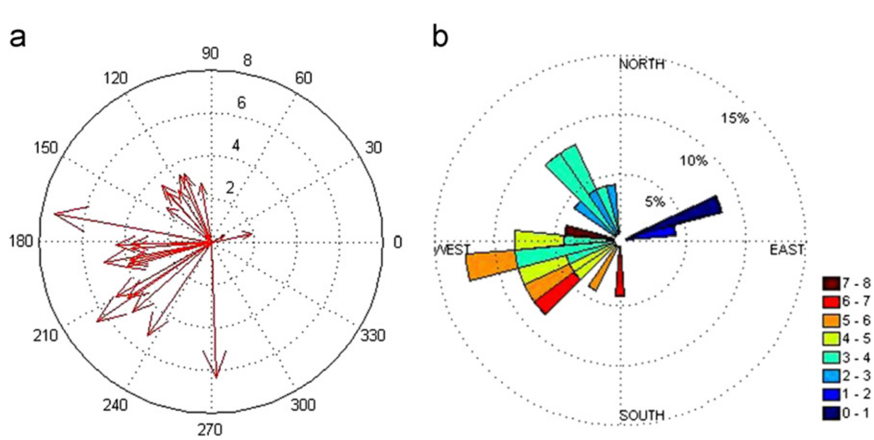

Fig. 11. (a) Monthly wind direction plot for 2010–2011 and (b) monthly wind rose plot for 2010–2011.

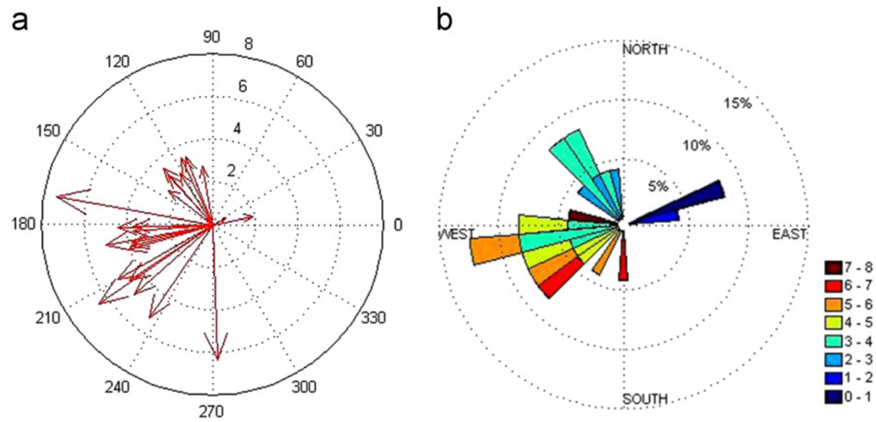

Fig. 12. (a) Wind direction plot (29th Sep 2010) and (b) wind rose plot (29th Sep 2010).

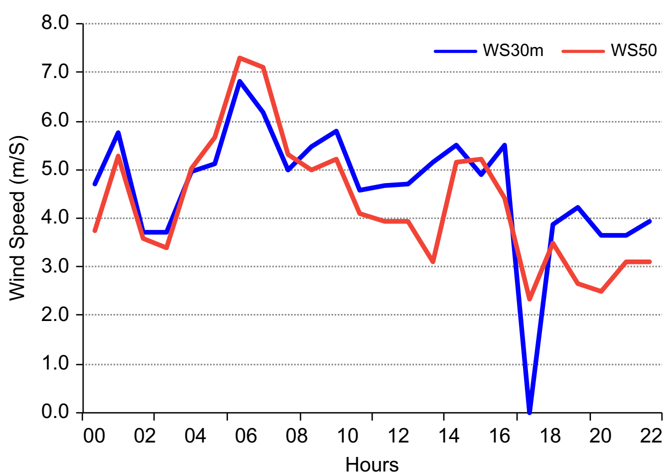

Fig. 13. Hourly wind speed variation on 29th Sep 2010.

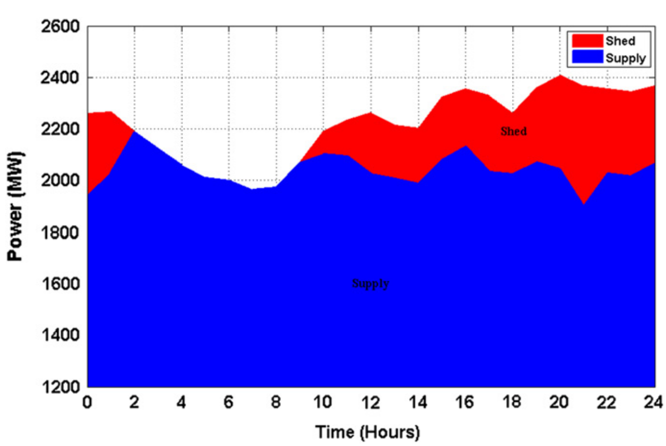

Fig. 14. Hourly load curve of Karachi on 29th September 2010.

Table 4
Hourly demand supply position in Karachi (on 29th sep 2010) and effects of windmills (with domestic consumers only).

Hours	Wind speed at 30 m (m/s)	Demand–Supply–Gap (MW)			Wind potential (MW)	
		Total demand	Total supply	Shed (−) excess (+)	Wind potential	Shed (−) excess (+)
0	4.7	2259	1939	−320	121.42	−198.58
1	5.8	2264	2029	−235	222.32	−12.68
2	3.7	2187	2187	0	60.20	60.20
3	3.7	2123	2123	0	59.24	59.24
4	5.0	2058	2058	0	142.70	142.70
5	5.1	2009	2009	0	157.88	157.88
6	6.8	1999	1999	0	370.97	370.97
7	6.2	1963	1963	0	274.69	274.69
8	5.0	1973	1973	0	144.43	144.43
9	5.5	2068	2068	0	192.45	192.45
10	5.8	2191	2101	−90	228.17	138.17
11	4.6	2232	2094	−138	112.35	−25.65
12	4.7	2260	2024	−236	118.34	−117.66
13	4.7	2213	2007	−206	121.42	−84.58
14	5.2	2200	1988	−212	160.67	−51.33
15	5.5	2322	2081	−241	194.57	−46.43
16	4.9	2354	2132	−222	137.58	−84.42
17	5.5	2326	2034	−292	195.63	−96.37
18	0.0	2259	2025	−234	0.00	−234.00
19	3.9	2357	2069	−288	67.26	−220.74
20	4.2	2406	2043	−363	88.51	−274.49
21	3.7	2364	1900	−464	57.34	−406.66
22	3.7	2353	2026	−327	56.87	−270.13
23	3.9	2342	2016	−326	71.53	−254.47

*All values are in MW.

purpose, the 29th Sep 2010 data from power utility company (KESC) and metrological department (PMD) is used as case study. This study will show that the wind mill installation by individual domestic consumers could result in decreasing the shed power (MW). For present case study, the hourly wind direction and wind rose plot, calculated at 100 m is plotted on MATLAB, as shown in Fig. 12.

Fig. 12 clearly shows that the area has a huge potential in West and South direction of around 210°. However the windmill could not be installed at greater height, thus the analysis is carried out at 30 m. The daily hourly wind speed (m/s) measured at the height of 30 m and 50 m on 29th Sep 2010 is shown in Fig. 13 [43].

From the power utility KESC, the hourly supply–demand data is also collected for the day of 29th Sep 2010, shown in Fig. 14 [45]. The hourly power demand-supply position on 29th Sep 2010 in Karachi is also given in Table 4.

From Fig. 14, it could be observed that the peak load is 2406 MW whereas only maximum 2043 MW is being supplied. This clearly shows that the KESC is not unable to meet the load demand of the consumers. In this paper it is suggested that the distributed wind energy can be utilized for electricity production in distribution system. 2 kW windmill is used as an example for distributed energy source. Wind potential of 2 kW windmill system is calculated using Eq. (2) and wind speed data at 30 m height is used. ρ is taken as 1.225 kg/m^3 at sea level, 59.3% mechanical efficiency, 20% electrical efficiency, diameter of windmill considered 3.5 m (commercially available 2 kW windmills) [46].

Table 4 is also presenting the net reduction in shed portion of supply due to incorporation of wind. The hourly availability and power shed due to wind and without wind mill for 29th Sept 2010 is plotted in Fig. 15 (+ve quantities are taken as excess while –ve quantities taken as shed).

From Fig. 15, it can be observed that the demand–supply gap have reduced considerably with installation of 2 kW windmill by residential consumers. However in the above analysis, the number of consumer chosen was 100%. The effect of number of domestic consumers installing wind mills on total daily energy saving is shown Table 5. The data of number of domestic consumer is taken from [3].

From Table 5, it can be observed that an enormous amount of fuel could be saved with installation of windmills. Here 2 kW windmill is used as an example, however higher rating windmill will give higher energy saving. The saved energy could be directed towards industry use. The cost details of installing wind turbine (as per wind consultant [47]) with all its accessories including cost of tower and cost of inverter for different residence is given in Table 6. Table 6 is also showing the individual necessary practicing details of installing windmill for residential purpose in Karachi. These details are found out from the consultant through a questionnaire [47]. The questionnaire used is given in Appendix A.

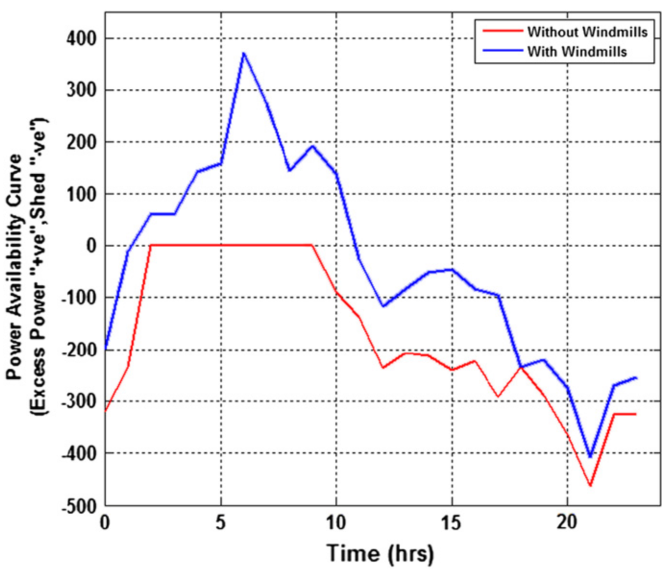

Fig. 15. Power availability graph due to wind on 29th Sep 2010.

Table 5
Energy saved due to wind.

Domestic consumers nos. (%age)	Daily saved energy (MW h)
15,82,403 (100%)	3356.54
11,86,803 (75%)	2517.41
7,91,201 (50%)	1678.27
3,95,600 (25%)	839.13

7. Challenges in implementing wind mills for domestic consumers

The power shortage problem in Karachi could be highly reduced with the installation of wind mills by individual residential consumers. However, there are few concerns regarding installation of wind on such a large scale by residential consumer. Those issues are discussed here briefly:

7.1. Cost

The initial cost of buying and installing a windmill is very high, although its life-cycle cost is lower than a conventional diesel or gas generators [48]. According to State Bank of Pakistan report 2012, the monthly per capita income of a consumer is only 2935 Rs (annual 35219 Rs) [49]. In this scenario, buying and installation of expensive windmill is out of reach for a consumer. Thus the local windmill industry has to be grown in the country. Competitors should come in the market with low cost and optimum windmill design. This will reduce the initial cost of windmill generator. The market trend shows that with the increase in rating of wind mill the cost of wind-mill decreases. Thus one possible solution to reduce the high initial cost of windmill is that the nearby residential consumer install windmill on sharing basis as shown in Fig. 16.

In wind mill installation, the other major cost includes cost of battery and cost of inverter, although some low cost components are also available in the market. If consumer initially pay good amount, the long life and less maintenance will reduced the lifetime cost. For example, the normal life of a battery is far less than the life of a deep-charging battery. However, the initial cost of deep-charging battery is much higher than the normal battery. Thus the cost of replacement in case of normal battery will highly burden the consumer [28].

7.2. Proper site survey

In windmill placement, it is very important to have a proper site details. The wrong survey could results in reduced power output than the estimated one. For example, in some areas having nearby high rise buildings are not favorable for windmill turbines due to wind shear and turbulence effect. The effects of both wind shear and turbulence on wind power output diminish by placing the machine sufficiently high above the ground level [50]. Such areas should be marked and the consumer should have the knowledge of available wind potential. Currently PMD are taken site details in some specific areas which could be extended to all over the city.

Table 6
Installation details and requirements.

Item	Details
Average cost/kW (excluding civil and transport work)	306,000 PKR (3200 USD)
Cost of replacing battery	25,000 PKR (270 USD)
Life of turbine	15–20 years
Life of battery	10–12 years
License	No need any permission or license
Commercial sizes of wind mills	500 W–30 kW
Poles of wind generators	4 or 6 poles
Diameter of rotor blades in residential area	Rotor diameter depends on the size of generator and blade aerodynamics
Height of tower on a two-storey bungalow	Standard requirement is 30 feet (From top roof level with respect to surrounding buildings)

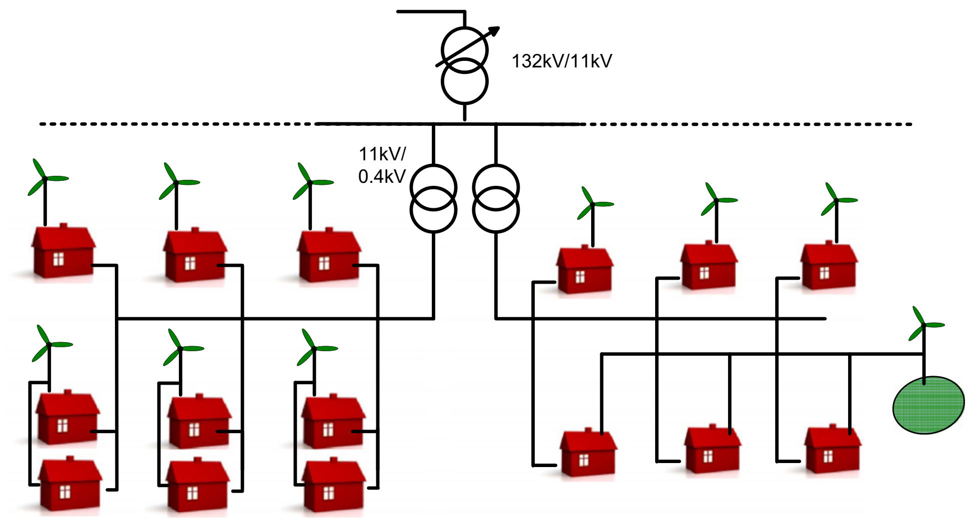

Fig. 16. Strategies to reduce windmill initial cost for residential consumer.

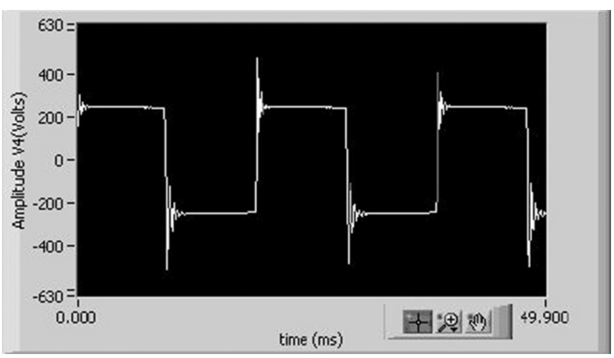

Fig. 17. Output voltage waveform from inverter.

7.3. Power quality

Quality of power is one the most important issues in power system. Non-sinusoidal output waveform from the wind output affect the life of appliances and increases the core losses [51]. Commercially available low cost inverters have very poor power quality, one of the inverter output measured in laboratory is shown in Fig. 17. The present need is to have some mandatory standards of power quality for the windmill generator output and must be followed.

7.4. Zoning

In erecting wind mill, care has to be taken that zoning regulations has been considered. Consent from the respective authority should be taken, if necessary. This is particularly important in high security and no fly-zone area. Consent of the neighbors should also be taken thus, in future there is no legal issues, regarding noise and visual impact of the windmill. Karachi is a big cosmopolitan city with some high rise buildings, in such cases it is necessary to properly evaluate the wind potential at that site. However it would be unfortunate if a high rise building in the neighbourhood is constructed later. Thus in planning of windmill installation, the correct marking of site is very important otherwise, the invested money could be lost. During operation, low flying birds could strike the turbine blades which could result in death of valuable species life [52]. With turbines threatening some bird and bat populations, researchers are seeking ways to keep the skies safe for wildlife [53]. Techniques have been discussed [54,55] to reduce the death impacts of flying birds and bats which includes:

1. Altering turbine speed reduces bat mortality at wind-energy facilities
2. Installing wind turbines in areas of low prey density may reduce raptor collision rates at wind facilities.
3. Using newer monopole tubular support towers rather than lattice support towers associated with older designs may reduce raptor collision rates at wind facilities.

7.5. Health impacts

In previous research [56,57], the authors have indicated that the low frequency noise from wind mill have adverse affects on human health. However, here it should be remembered that such noise does not causes any hearing loss. Such low frequency noises resulted in distress and uncomforted of mind and body. However, the research is carrying out to improve the mechanical structure of windmill and reduce the noise output. These problems could be overcome by carrying out more research in designing and improving the standards of windmill design.

7.6. Development of Standards for domestic windmill installation:

The present need is to have some country regulations in constructing, erecting or placing wind mills. Currently no such standards exist for domestic power consumers in Pakistan. However the standards proposed by European Union countries, for example Irish wind-power industry, could be considered as basic guidelines in erection of wind-mill turbine within the curtilage of a house [58]. However for roof or building mounted turbine, an application to your local authority through the normal planning mechanism is required.

8. Benefits to power utility company (KESC) and electricity consumers

The introduction of small wind-mills offers some advantages to utility as well as to consumers also. These are discussed below.

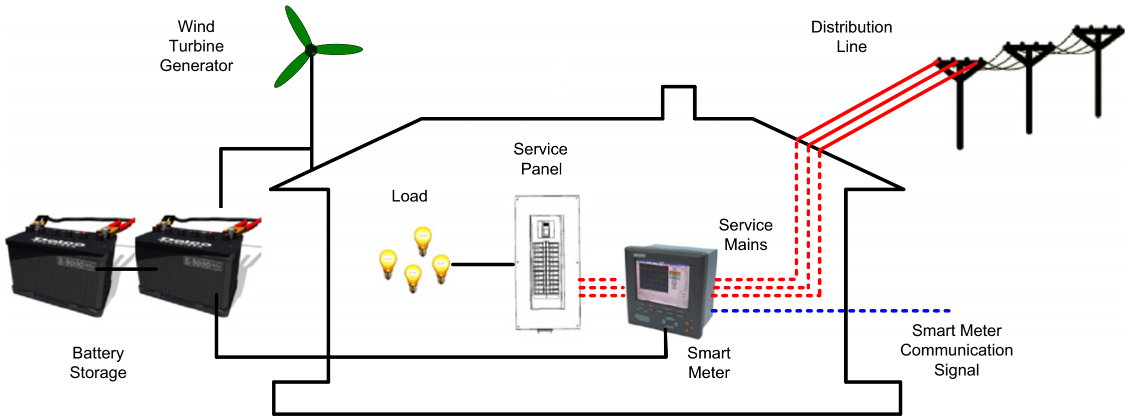

Fig. 18. Smart grid concept.

Table A1
Monthly wind speed (m/s) at 30 m [43].

Month	2002				2003				2004				2005			
	Max	Mean	δ	Variance	Max	Mean	δ	Variance	Max	Mean	δ	Variance	Max	Mean	δ	Variance
Jan	–	–	–	–	15.65	1.39	1.87	3.48	35.54	2.32	2.24	5.01	9.53	1.53	1.82	3.34
Feb	–	–	–	–	11.82	2.25	2.40	5.78	13.36	1.68	1.89	3.57	10.3	2.17	2.27	5.16
Mar	–	–	–	–	11.82	2.38	2.27	5.17	11.82	4.01	2.32	5.38	27.13	3.10	2.58	6.65
Apr	10.99	3.55	2.18	4.76	12.59	3.25	2.56	6.55	14.12	6.16	2.24	5.02				
May	14.8	5.37	2.49	6.21	11.82	4.62	2.25	5.04	12.59	6.65	2.38	5.66				
Jun	13.36	4.80	2.13	4.54	16.42	4.94	2.25	5.08	19.48	7.70	3.02	9.12				
July	13.36	5.64	2.06	4.24	20.24	3.49	3.36	11.28	16.42	6.61	2.13	4.55				
Aug	16.42	3.70	2.31	5.32	16.42	4.08	2.60	6.79	14.96	5.83	1.78	3.19				
Sep	11.82	4.75	1.81	3.28	20.24	3.55	2.63	6.90	11.06	3.95	2.12	4.48				
Oct	9.53	0.91	1.72	2.96	10.3	1.25	1.74	3.04	15.21	2.40	2.42	5.85				
Nov	9.53	0.99	1.66	2.76	8	1.49	1.76	3.09	8	1.31	1.61	2.58				
Dec	14.39	1.44	1.92	3.70	10.3	1.77	1.84	3.38	16.42	2.14	2.57	6.62				

8.1. *Meeting power demand*

In previous Section 2, it has been observed that the major percentage of electricity consumption in KESC system is due to residential load. This approach of encouraging residential consumers for installation of wind-mill will reduce the demand–supply gap and also save the country capital in buying expensive heavy expensive oil for thermal power generation. Saved power could be directed to industry for the better interest of country.

8.2. *Transmission line congestion and future cost*

In Karachi as well as in Pakistan, the transmission line network is very old and fully loaded. The city population as well as electricity demand is increasing[59]. In this scenario, distributed wind generation will highly help in avoiding transmission line congestion and deferring the cost of new transmission lines.

8.3. *Eco-friendly environment*

The introduction of green energy based distributed power generation will enable the use of less fossil fuel and thus helps the authorities in making clean and polluted free environment. Authors in [60,61] have indicated that wind energy is a clean, eco friendly and cheaper source of energy as compared to other renewable energy sources. It has also been found that wind energy has minimal impacts on local habitat as compared to other sources of energy.

8.4. *Carbon credit*

Carbon credit is a way to assign a quota to an industry or a country to reduce greenhouse gasses emission in the atmosphere. The non-utilized carbon credits sell in an open market and thus earn money [62,63]. By installation of clean fuel wind mills, the country as well as KESC could save carbon points and utilize the earned credits for better infrastructure.

8.5. *Reducing line losses and increasing system capacity*

By incorporating small wind mills in the residential system, line power losses could be reduced. Right now there are overall 32.10% power losses including technical as well as non technical power losses [3]. Reduction in line losses will also results in more transfer of electrical power through same transmission line infrastructure.

8.6. *A way to smart grid*

The future of power system is smart grid networks. The basic concept of smart grid network is shown in Fig. 18. In smart networks, the consumer could be benefitted in terms of bi-way power flow. In case of excessive power available to the consumer, the consumer could sale the available power to the utility particularly during off-peak hours. However the issues related to power quality, billing technology, metering technology, transmission and handling of huge communication data, possible security and protection problems needs to be addressed [64,65].

The research presented in this paper could be the first mile stone in future smart-grid networks.

8.7. Reliable power

Due to demand–supply gap in the city, KESC follows a schedule load shedding policy i.e. when the load exceeds from available power, a load shedding plan is followed. Some feeders are de-energized for specific period of time to maintain the balance between load and supply. Consumers need to install battery-inverter based uninterruptible power supply system or standby power generations. By installation of wind mill, user did not need to spend extra money in purchase of UPS or standby generator for power shed duration. Available wind power could be utilized for load shedding period.

8.8. Reduction in electricity bill

In the last few years, the cost of electricity in all over the country particularly in Karachi has been exponentially increased. One of the major identified reason, for such a tremendous increment in tariff, is major rely of KESC on thermal power generation [3]. In such a high fluctuating oil market, windmill power will highly reduce the electricity bill for residential consumers. Karachi is a highly populated city and the city population is increasing. The culture of high rise apartment system is also increasing. The wind potential at the top of high rise building could also be utilized to power the outdoor lighting of apartments which will also result in monthly financial saving.

In summary, installations of windmill by individual residential consumers are useful to utility as well as to consumer also. It is also possible to develop windmills on large scale and integrate to the existing power system. This approach have some technical challenges also, including less efficiency, high-cost of generation, transfer of wind-power from remote area to the consumer end, transmission loses and others [66]. Household self-power generation could be first step towards smart-grid policy implementation. In smart-grid, residential consumers with self power generations could sell the non-utilized power to the utility. All the information related to information on energy consumption, energy generated and consumer-utility billing details will be available from smart meters. In some countries like UK, the smart grid policy implementation has been started. In October 2008, the Government announced that smart meters were to be installed in every home in Britain by the end of 2020. The program will involve the replacement of more than 50 million electricity and gas meters in over 29 million homes and businesses. In March 2011, the 2020 deadline was brought forward to 2019 [67].

9. Conclusion

In this paper, wind statistical analysis is carried out using SPSS software on four year wind data. The statistical result shows that the wind speed is quite good for generating wind power. For example in 2010–2011, the monthly mean wind speed at the height of 10 m is found in the range of 5.3 m/s to 8.0 m/s. However efforts are needed from the government–private partnership to utilize that potential.

In this paper, it is also proposed that the power shortage in Karachi can be reduced by incorporating small residential windmills in domestic sector. From the case study, it has been found that 1678 MW h of energy could be saved on daily basis, if 50% residential consumers installed small 2 kW residential windmills. The saved power could be directed for industrial usage.

Technical and non-technical issues related to installation of small residential wind mill are also discussed in the paper. The major issues regarding cost and efficiency could be resolved if wind mill industry grow and multiple competitors with their own efficient windmill design come in the market. Residential windmill installation will benefit to the consumers in terms of higher reliability and reduced electricity bill. The utility will also be benefited in terms of meeting demand–supply gap, reducing transmission line losses, avoiding transmission line congestion and other economical benefits.

Acknowledgment

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Appendix A. Questionnaire

See Appendix Table A1.

Questionnaire to the residential wind suppliers:

- What are the commercial sizes of wind generators available and their costs?
- What is the diameter of blades in residential area?
- How many poles does a wind generator have?
- What is the cost of wind turbine with all its accessories, cost of tower and cost of inverter?
- What is the average life of battery and life of turbine?
- What is the average life of wind turbine?
- In Karachi, what is generally the height of tower on a two-storey bungalow?
- Which localities or areas have the maximum wind speed?
- Do we need to take any permission (or license) from the government, to set up a wind turbine at our home? If we do then what is the cost of this license.

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